NMR-BASED MAGNETIC FIELD MEASUREMENT SYSTEM

DESIGN REPORT

Approved by:
Dr. G.N.Kulipanov BINP Deputy Director

Developed by:

Dr. A.S.Medvedko Head of Radiophysics Division

G.V.Karpov Staff scientist

E.I.Shubin Staff scientist

TABLE OF CONTENTS.

PART 1. GENERAL DESCRIPTION.

1.1. INTRODUCTION.

The Nuclear Magnetic Resonance Field Measurement System (NMR System) is intended for precise measurement and stabilization of the permanent magnetic fields.

The System is made in the VME standard. All its modules occupy 4 slots. A VME Controller Motorola MVME-2401 controls of the Magnetometer operation, reads and processes of the Data. The software attached is intended for work in the VxWorks operational system.

1.2. CONFIGURATION OF THE NMR SYSTEM.

A set for 12-channel NMR system includes 4 VME modules, 12 preamplifiers, 12 NMR probes, 10 cables for block-to-block connections in the VME crate and 24 cables for external connections with the preamplifiers and probes.

VME modules :

- NMR Synthesizer	1 size
- NMR Controller	1 size
- NMR Receiver	1 size
- NMR Multiplexor	1 size

The software is made for a VME controller Motorola MVME-2401.

The Preamplifiers locate close to the site of measurement on the magnet body. The input of the Preamplifier is connected to the NMR probe by a short (not more than 2 m) RF cable. There must be 1 preamplifier and 1 probe per channel. All the cables connecting the Preamplifiers with the VME modules are decoupled with the VME ground for a voltage of 500V.

1.3. TECHNICAL CHARACTERISTICS OF THE NMR SYSTEM.

2.1.	Field range.	250 ÷ 2000 Gs
2.2	Maximum admissible gradient of the measured field	0.5 G/cm
2.3.	Relative accuracy of measurements	
2.3.1	With field gradient less than 0.2G/cm with whole measurement time (for 12 channels) T=10 sec	10 ppm
2.3.2	With field gradient 0.4G/cm with whole measurement time (for 12 channels) T=10 sec	30 ppm
2.3.3	With field gradient less than 0.2G/cm with whole measurement time (for 12 channels) T=1 sec	30 ppm
2.4	Number of channels	12
2.5	Whole measurement time	
	with 5 storages of the signal	1 sec
	with 50 storages of the signal	10 sec
2.6.	Multi-channel measurement	
2.6.1	Schedule of measurement - sequential – from channel to channel.	
2.6.2	Programmed channel selection	
2.7.	Modes of operation	
2.7.1	Search mode - scanning through the field range and search of the NMR signal	
2.7.2	Measurement mode - measurements of field and tracking of the measured field	
2.8	Scanning rate during the search mode for all 12 channels	0.5 G/sec
2.9	Maximum admissible distance from the VME crate to the Magnets	300 m
2.10	Probe dimensions	
	body dimensions	9.5×15×35 mm
	sensitive area	5×5×10 mm
2.11	Number of the VME modules	4
2.14	Insulation voltage between the VME ground and probes:	500 V
2.15	Power consumption from the VME crate Power Supplies	
	+6 V	3 A
	+12 V	0.6 A
	-12 V	0.2 A

1.4. SHORT DESCRIPTION OF NMR TECHNIQUE .

The pulsed NMR technique is used for measurement of magnetic fields.

If hydrogen nuclei or other nuclei with magnetic moments are placed in permanent magnetic field, they will start, due to the magnetic moments, precessing motion with frequency depending of field magnitude. Precession phases of different nuclei differ in the equilibrium state. If the nuclei are affected by a short pulse of an RF field of a certain amplitude with frequency close to the precession frequency, precession phases of the nuclei will be equal on completion of the pulse. If these nuclei are inside a coil, one can watch in the ends of the coil a signal with a frequency equal to the precession frequency of nuclei F_{nmr}. The spins interact with each other, which makes their precession phases change in a random way. That is why amplitude of the signal will decay in time with a time constant, called the time of spin-spin relaxation. Since a constant magnetic field is inhomogeneous, precession frequencies of nuclei of different parts of the sample space will differ, which will cause a faster decay of the signal (Fig.1).

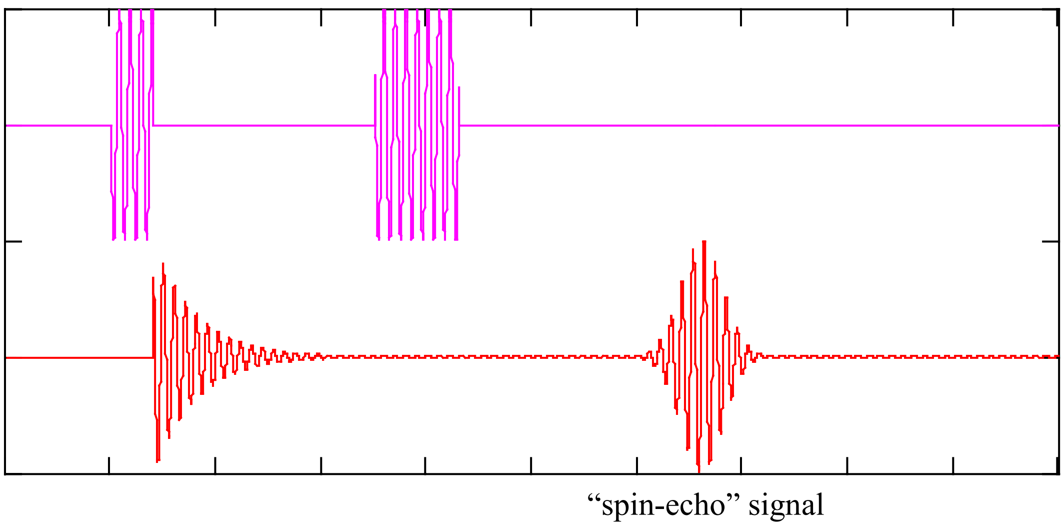

Fig.1. NMR technique.

If in time T after the end of the RF pulse one excite of the nuclei with the second RF pulse with double pulse duration in time T after the second RF pulse precession phases of the spins will be the same. So called "spin-echo" signal will appear.

Measuring frequency of the "spin-echo" signal F_{nmr}, one can determine magnitude of the magnetic field B:

$$B = F_{nmr}/\gamma.$$

where B - magnitude of the magnetic field,

γ - the gyromagnetic ratio.

The gyromagnetic ratio γ is a physical constant depending on the type of nuclei. For protons γ=42.57639 MHz/T. [1]. An increase in homogeneity of the permanent magnetic field leads to a decrease in duration of the "spin-echo" signal and, as a result, to decrease of measurement accuracy.

NMR signal is recorded by ADC and then is processed by VME Controller. The main procedure of the signal processing is Fast Fourier Transformation. Then the top of the signal spectrum is cut off at the half height of the maximum and frequency corresponding to the half of full integral of this cut-off part of the spectrum is determined .

1.5. DESCRIPTION OF OPERATION OF NMR SYSTEM.

A functional diagram of the NMR System is presented in Fig.2. Time diagrams, explaining its operation, are depicted in Fig.3. The main functional parts of the NMR System are: frequency synthesizer (NMR Synthesizer), power amplifier, variable gain amplifier (VGA), RF switches, 2 mixers, 2 ADC, NMR controller, Probe Multiplexer, Preamplifiers and probes. Operation of all parts of the system is controlled at two levels:

1) from the VME Controller through VME bus
2) from the NMR Controller by control signals applied to other modules through the connectors on the front panels.

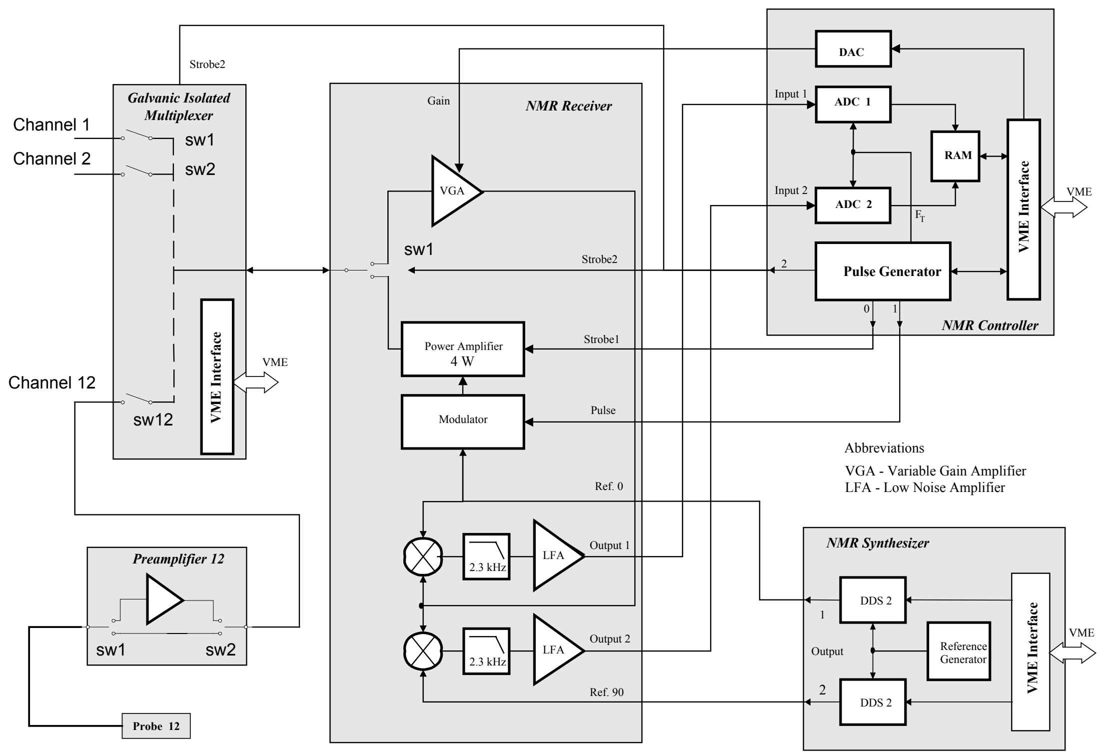

Fig 2. Functional diagram of the NMR System.

The VME Controller sets time parameters of the NMR Controller, frequency of the NMR Synthesizer, required gain of the VGA, switches on the channel selected by the Multiplexer and reads data from the ADC memory. Besides that, the VME Controller sends a start command to the NMR Controller, starting an operational cycle. Full operational cycle consists of N elementary cycles, where N is number of storages. In each elementary cycle one “spin-echo” signal is recorded. “Spin-echo” signals from different elementary cycles are summed up. Since phases of these signals are identical, such a summing allows in $\sqrt{N}$ times increase of the signal/noise ratio. After the start command from the VME Controller and till completion of the elementary cycle the NMR System operates under control of the NMR Controller and the VME Controller waits the completion of the elementary operational cycle. The NMR Controller controls of the another parts of the NMR System with the help of three signals coming from its control outputs 0-2 (Fig.2). The signal from output 0 supplies the power amplifier. The signal from output 1 forms the envelope of the RF excitation pulse. The signal from output 2 controls the RF switch of the NMR Receiver and switches of the Preamplifier of working channel.

Two main tasks are performed within elementary cycle:

1) generation of RF excitation pulses and transmission of them to the coil of the NMR probe.

2) reception of the NMR signal from the coil of the probe, amplification of it, detection and recording with the help of the ADC.

In Fig.3 two elementary operational cycles are depicted. Assume that only the channel 12 is working. In the initial state, immediately after start of the cycle (Fig.3), there is high-level voltage at the outputs 0,1,2 of the NMR Controller. Switch 1 of the NMR Receiver, switches 1,2 of the Preamplifier are in upper position, switch 12 of the Multiplexer is closed, switches 1÷11 of the Multiplexer are opened. Such a state of the switches corresponds to the reception mode. Sampling pulses come to the ADC. Noise is recorded. In 20 30 microseconds before the front edge of the excitation pulse, clock pulses cease to come to the ADC, low-level voltage is set at the outputs 0 and 2 of the NMR Controller, switch 1 of the NMR Receiver, switches 1,2 of the Preamplifier turn into lower position. Beginning of the exciting pulse corresponds to the low-level voltage appearing at the output 1 of the NMR Controller. The transmission mode begins. RF voltage from the NMR Synthesizer comes to the coil of the NMR probe through the limiting amplifier, modulator, power amplifier, switch 1 of the NMR Receiver, switch 12 of the Multiplexer, connecting cable and switches 1,2 of the Preamplifier 12. In the end of the excitation pulse again high-level voltage is set at the NMR Controller outputs 0, 1, and 2, which stops applying RF voltage to the coil of the probe. In such a way the first RF excitation pulse is formed. In time T after first excitation pulse the second excitation pulse with double length is generated. In 400-800 microseconds after the second excitation pulse, sampling pulses come to the ADC again. NMR signal is recording to the ADC. The NMR signal with frequency F_{NMR} from the coil of the probe comes through switch 1 of the Preamplifier 12 to the low-noise amplifier of this Preamplifier with gain factor about 40 db. From the low-noise amplifier, through the switch 2 of the Preamplifier 12, connecting cable, switch 12 of the Multiplexer, the signal arrives to the variable gain amplifier (VGA). From the VGA the signal comes to two identical mixers. Reference RF voltages, shifted by 90 degrees relatively to each other, arrive from the frequency synthesizer to the another entries of these mixers. After passing through the low-pass filters with a cut-off frequency of 2.3 kHz and amplification by low frequency amplifier (LFA) signals depicted in Fig.3 will appear at the outputs of both channels (Output 1 and Output 2).

Frequency of the signals will be F_d:

$$F_d = F_{NMR} - F_{synt}$$

where F_{NMR} - frequency of the NMR signal,
F_{synt} - frequency of the Synthesizer.

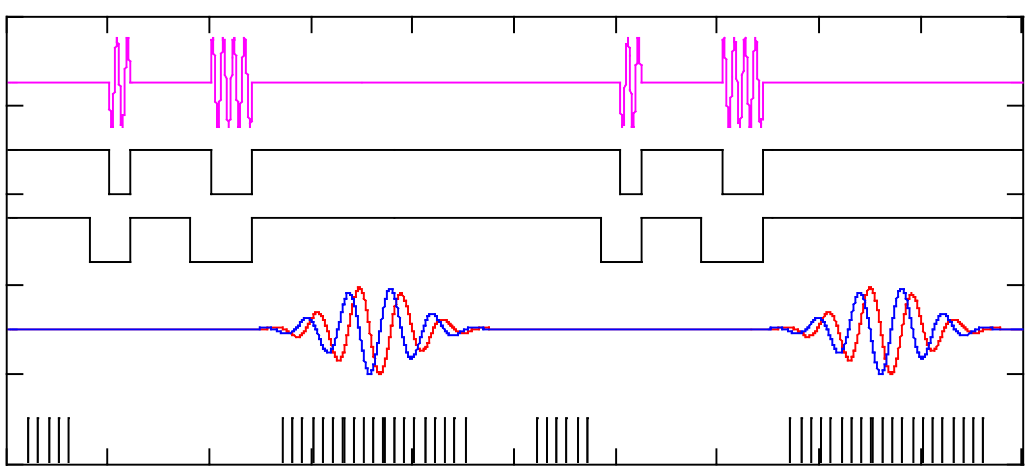

Fig 3. Time diagrams for two elementary cycles.

These signals arrive to the inputs of ADC1 and ADC2, where they are transformed into arrays of numerical codes and recorded to the memory. Sampling frequency equals 8 kHz. The signal recorded will locate in the beginning of the memory area in the cells with numbers 0, 1, 2 etc. After completion of recording of the signal the microcontroller sums this signal with the earlier-stored signal, locating in memory cells 768, 769 etc. This is the end of the elementary cycle.

Then elementary cycle is repeated N times. After completion of the full operational cycle NMR Controller returns control to the VME Controller. The VME Controller reads information from the ADC memory and then processes it. Processing of information includes analysis of presence of the NMR signal and finding out of difference frequency F_d. Quadrature processing of the signal allows determination of module and sign of the difference frequency F_d. The NMR frequency F_{NMR} is determined by summing up the difference frequency F_d and Synthesizer F_{synt}:

$$F_{NMR} = F_d + F_{synt}.$$

In order to decrease the influence of regular interference to the NMR System operation and to simplify analysis of presence of the NMR signal, noise of the receiving part of the System is additionally recorded. Noise is recorded before the frond edge of the first excitation pulse (Fig.3). Unlike the NMR signal, the noise will be the same during both the recordings, which permits one to recognize it easily.

1.6. ORGANIZATION OF MULTICHANNEL MEASUREMENTS.

More preferable way of organization of multichannel measurements is represented in Fig.4.

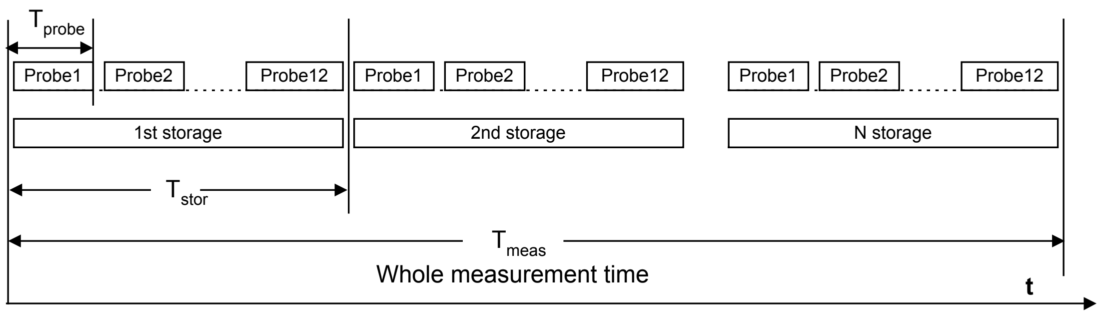

Fig 4. Time diagrams for multichannel measurements.

Time interval T_{probe} includes only 1 elementary cycle for one of the probes. After completion of the elementary cycle for the probe 1 (channel 1) channel 2 is set in the Multiplexer. Then the elementary cycle is repeated for channel 2. After scanning over all working channels (after time T_{stor}) this process is repeated N times to perform N storages. Time interval between elementary cycles for some probe have to be more than relaxation time to recover nuclear magnetization of this probe. Usually it is about 100÷200 ms. In presented method this time is used for elementary cycles for another probes. Within the interval between storage number j and storage number j+1 probe number k completely recover its nuclear magnetization.

1.7. DESCRIPTION OF THE PRINCIPLE OF DATA PROCESSING.

Data processing includes 3 steps:
- primary processing
- analysis of presence of the NMR signal
- finding out the difference frequency F_d and the value B of the measured field.

1.7.1. Primary data processing.

In the beginning of this step, 2 complex arrays are formed from the data array read from the memory of the ADC. The 1st array corresponds to the recording before the excitation pulse. The 2nd array corresponds to the recording after the second excitation pulse, i.e. during the expected appearance of the NMR signal (Fig.3). Then the 2nd array is multiplied by a weight window - a "Hemming" window and is completed with zeroes to 256 points.

1.7.2. Analysis of presence of the NMR signal.

To perform this procedure 2 auxiliary arrays with a less number of points are formed from the two original arrays. As a rule, number of points doesn't exceed 16, which allows shortening of the analysis time. Then fast Fourier transformation (FFT) of both the auxiliary arrays is performed and the first array is subtracted from the second one. Since the noise spectrum is the same in both the arrays and the signal spectrum is contained in the second array only, the difference array obtained after the subtraction will contain the signal only, not noise. After that, the ratio of the maximum of the difference array to the maximum of the first array is determined. An indication to the NMR signal will be an excess of this ratio over some set threshold. Another indication to presence of the NMR signal is an absolute excess of the signal amplitude over a set threshold. The next step of the processing is performed only in presence of the NMR signal.

1.7.3. Finding out the difference frequency F_d and value B of the measured field.

The main procedure of this step is fast Fourier transformation of the second original array obtained after the excitation pulse. Then the top of the signal spectrum is cut off at the half height of the maximum and frequency corresponding to the half of full integral of this cut-off part of the spectrum is determined. That is the result frequency F_d. Its sign can be both positive and negative, depending on the sign of the difference of the NMR and synthesizer frequencies (F_{NMR}-F_{synt}):

$$F_{NMR} = F_d + F_{synt}.$$

Magnitude B of the field being measured is determined by multiplying the NMR frequency by the gyromagnetic ratio γ :

$$B = \gamma \bullet F_{NMR}.$$

1.8. SHORT DESCRIPTION OF THE MODES OF OPERATION.

The NMR System has two modes of operation: measurement mode and search mode.

In the measurement mode the System cyclically performs field measurements scanning over selected channels. Synthesizer frequency tracks to the measured field. This mode is possible if the difference between synthesizer frequency and NMR frequency is less than 2÷2.5 kHz, otherwise NMR signal will be absent and the search mode will be required.

In the search mode Synthesizer frequency is scanning in the specifying range and checking of the NMR signal presence is performed. If the Synthesizer frequency will be close to NMR frequency (less than 2÷2.5 kHz) NMR signal will appear and measurement mode may be started.

PART 2. DESCRIPTION OF THE VME CARDS.

2.1. NMR CONTROLLER .

2.1.1. FUNCTIONS OF THE MODULE

1) Generation of control pulses for the switches of the Preamplifier, switches of the Receiver Multiplexor and switches of the Transmitter Multiplexor. These signals provide conversion of the NMR system from the reception mode to the transmission one and vice versa.
2) Analog-to-digital conversion of signals from the outputs of the module NMR Detector.
3) Summing of signals from different elementary cycles.

2.1.2. PARAMETERS.

2.1	Time resolution of control pulses	1μs
2.2	ADC resolution	12 bits
2.3	Clock frequency of ADC	250 kHz
2.4	Range of input voltage of the ADC	±5 V
2.5	Data memory capacity	8K
2.6	Minimal duration of an elementary cycle	2.5 μs
2.7	Voltages on digital outputs	TTL levels
2.8	Number of digital outputs	5
2.9	Dimension of the module	1 size
2.10	Consumption	
	+5 V	0.5 A
	+12 V	0.03 A
	-12 V	0.05 A

2.1.3. FRONT PANEL.

There are 8 connectors of the LEMO type and 1 light diode on the front panel.

The «CYCLE» light diode displays the operational cycle.
Connectors 0-4 - outputs 0-4
Connector "F" - output of the 10 mV 12 MHz test signal
Connectors «INPUT 1», «INPUT 2» - analog inputs

2.1.4. ADDRESSES OF FUNCTIONAL UNITS AND FUNCTIONS OF THE MODULE.

Address 4 low-order bits	Functional unit or function	word length
0x0	DATA RAM (writing and reading)	8
0x2	Program RAM (writing and reading)	8
0x4	Address Counter (writing)	16
0x6	Address Register (writing)	16
0x8	Start of Cycle (writing)	8

0xa	Stop of Cycle (writing)	8
0xc	Checking of cycle presence	8
0xe	Status register (writing and reading)	8

A variant with short address A16 is realized in the module. Codes of the address modifier are 0x29 и 0x2d.

High-order addresses (A4-A15) in the VME address space are set by jumpers (J1-J12) (see Fig.1). Bit = 0: jumper on, bit = 1: jumper off.

A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15
J12	J11	J10	J9	J8	J7	J6	J5	J4	J3	J2	J1

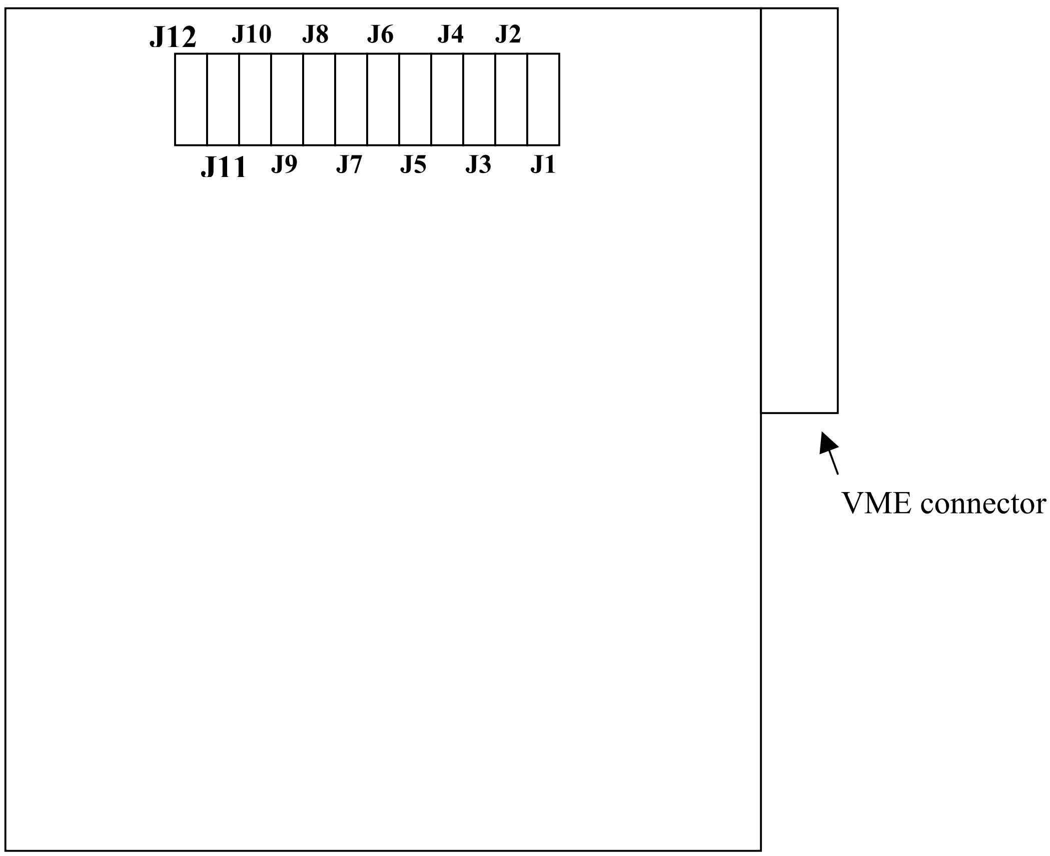

Fig. 5. Positions of jumpers on the board.

2.1.5. DESCRIPTION OF THE PRINCIPLE OF OPERATION

Functional diagram of the NMR CONTROLLER module is depicted in Fig.1. The module contains a Microcontroller, Data RAM, Program RAM, 2 ADCs, VME Interface.

After a cycle start pulse arrives through the VME interface, i.e. any cod is written by address 0x8, the operational program written in the internal ROM of the microcontroller starts. Digital outputs of the module and clock inputs of the ADC are connected to one of the ports of the microcontroller. A pulse sequence by some digital output is formed through writing zeroes and units to the corresponding bit of this port in assigned moments. Time discreteness is 1 μs. Besides forming control pulse sequences, the work program performs summing of arrays of signals from different elementary cycles. Reading from address 0xc is disabled during the operational cycle. After completion of the full operational cycle the operational program stops, the microcontroller waits arrival of the next start pulse. Reading from address 0xc stops being blocked and 0 is read from this address. After that, the VME controller reads contents of the Data RAM and processes the information obtained.

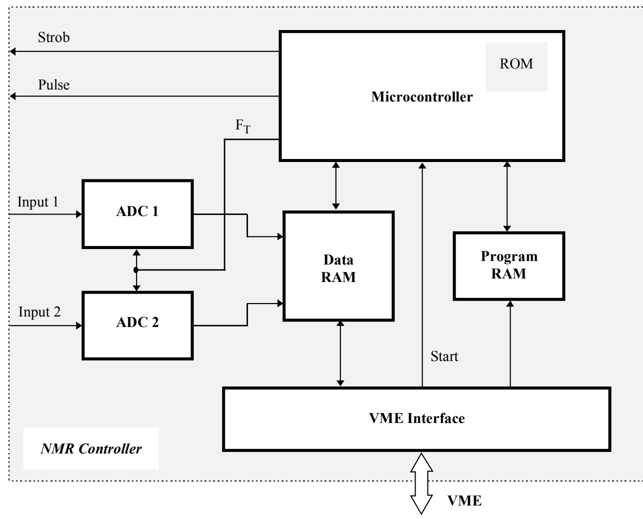

Fig. 6. Functional diagram of the NMR CONTROLLER

2.1.6. DESCRIPTION OF THE STATUS REGISTER.

6.1. Bit 1 sets operational mode of the microcontroller:
  0 - operation from the external Program RAM
  1 - operation from the internal ROM
Operation from the Program RAM is used to test the NMR system. In so doing, the test program is loaded to the Program RAM.

6.2. Bit 3 permits access to the Data RAM :
  0 - access inhibited
  1 - access permitted

2.1.7. WRITING OF PARAMETERS OF THE OPERATIONAL CYCLE.

Altogether there are 6 variable parameters of the operational cycle. They are recorded to the Data RAM to cells 0x200-0x206:

Cell number	Parameter
0x200	number of samples of the ADC before the excitation pulse (N1)
0x201	number of samples of the ADC after the excitation pulse (N2)
0x202	duration of the excitation pulse (T = 3∗cod [μs])
0x203	time from the end of the excitation pulse till arrival of clock pulses to the ADC (T = 3∗cod [μs])
0x204,	number of elementary cycles in the full operational cycle

0x205	(cell 516 contains the lowest-order bits)
0x206	duration of an elementary cycle (T = cod∗0.5 ms)

2.1.8. READING OF DATA ARRAYS.

8.1. The 3rd bit of the status register has to be set before reading of data arrays from the Data RAM.
8.2. The 1st byte of the data array is in cell 0x300.
8.3. Every sample contains 6 bytes: the first three bytes correspond to the signal at input 1 and the second 3 bytes correspond to the signal at input 1.

2.2. NMR RECEIVER

2.2.1. DESTINATION.

1.1. Amplification of the signal at high frequency.
1.2. Transmission of the NMR signal spectrum from the high frequency area to the low frequency area.
1.3. Amplification of the signal at a low frequency.
1.4. Forming of 4 W excitation pulses.
1.4. Commutation of the input from signal receiving to exciting RF pulse transmission.

2.2.2. PARAMETERS.

2.1	Gain of the VGA	20 ÷ 60 Db
2.2	Bandwidth of the VGA	80 MHz
2.3	Maximal signal amplitude at the VGA output at R_H=50 Ohm	1 V
2.4	Input impedance	50 Ohm
2.5	Gain factor of the receiving channel in the transmission mode	-80 ÷ -40 Db
2.6.	Input control voltage for VGA	0÷2.5 V
2.7	Bandwidth of the mixer	150 MHz
2.8	Cut-off frequency of the low-pass filter	2.3 kHz
2.9	Gain at a low frequency	60 Db
2.10	Inequality of the gain factors of the SIN and COS channels, not more than	3%
2.11	Phase mismatch of the SIN and COS channels, not more than	5 °
2.12	Output power of the Power Amplifier, R_H=50 Ohm	4 W
2.13	Bandwidth of the Power Amplifier	90 MHz
2.14	Control voltages of the digital inputs and outputs	TTL level
2.15	Module dimension	1 size
2.16	Consumption	
	+5 V	0.5 A
	+12 V	0.2 A
	-12 V	0.1 A

2.2.3. FRONT PANEL

There are 9 connectors of the LEMO type and 1 connector of the SMA type on the front panel.

Name of the connector	Connector type	Destination
«INPUT»	SMA	analog input
«OUTPUT1»	LEMO	analog output of the COS channel
«OUTPUT2»	LEMO	analog output of the SIN channel
«Pulse»,«Strobe1», «Strobe2»,	LEMO	digital inputs of the control signals
«REF.0»,«REF.90»	LEMO	Reference orthogonal RF voltages from frequency synthesizer
«VGA OUT»		VGA output for checking
«GAIN»	LEMO	Input control voltage to VGA

2.2.4. DESCRIPTION OF OPERATION.

A functional diagram of the NMR Receiver is depicted in Fig.5.

The NMR Receiver is not controlled through the VME bus. All control signals come to the module through the connectors «Pulse»,«Strobe1»,«Strobe2».

In the reception mode, high level voltages are applied to all control inputs: «PULSE», «Strobe1», «Strobe2». Switch 1 is in upper position. Gain of VGA is adjusted within the range 20-60 Db by a control voltage in the connector «GAIN» on the front panel. Power amplifier is locked, its power consumption close to zero. In the transmission mode, a low-level voltages at first come to the «Strobe1», «Strobe2» inputs. Switch 1 turns into lower position. Power amplifier became unlocked, its power consumption increases to 10÷15 W. In 50÷60 μsec after appearing of the low level voltages in the «Strobe1», «Strobe2» inputs low level voltage come to the «Pulse» input. This control voltage comes to the Modulator and forms the exciting RF pulse.
After the end of the exciting RF pulse all control voltages return to high level and module returns to the reception mode.

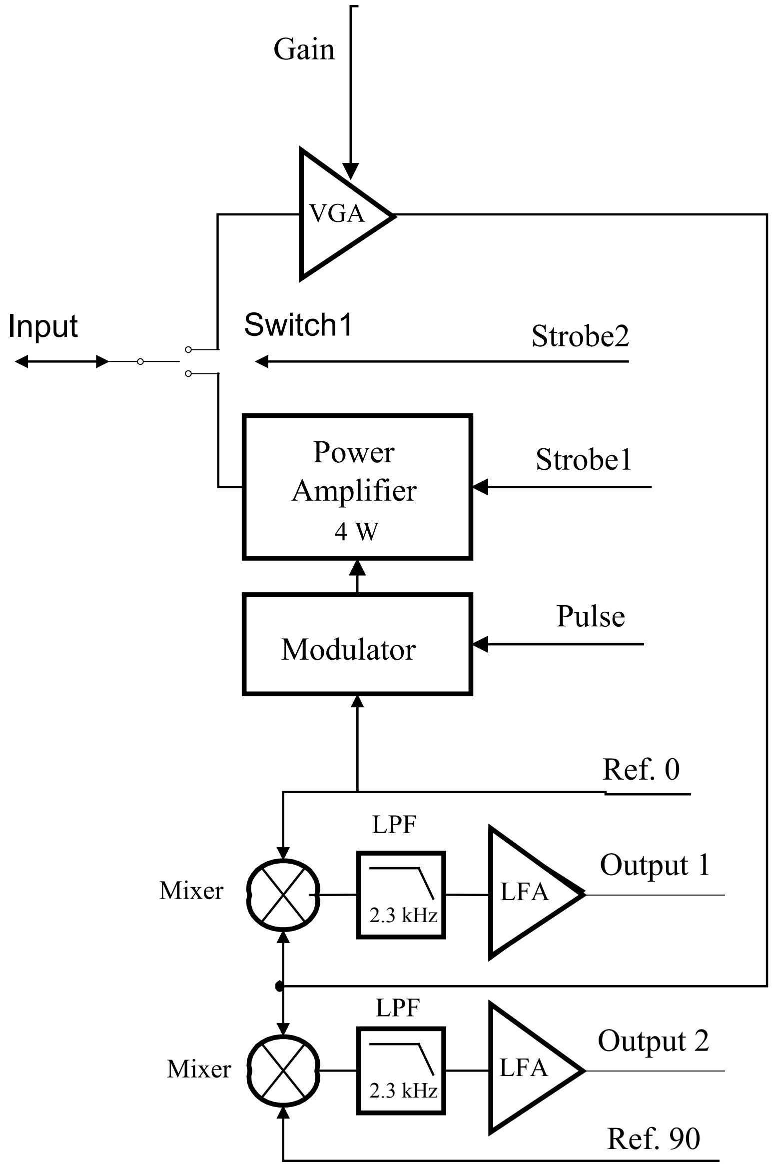

Fig. 7. Functional diagram of the NMR Receiver

2.3. NMR SYNTHESIZER

2.3.1. Destination

The NMR Synthesizer module is intended for operation as a part of the NMR magnetometer.

The synthesizer performs the following functions:

assignment of frequency of RF excitation pulses, in the excitation mode;

creation of an orthogonal signal with the frequency of nuclear magnetic resonance for the quadrature detector, in the reception mode.

2.3.2. Parameters

2.1	Frequency range	0.1÷40 MHz
2.2	Resolution of frequency tuning	0.04 Hz
2.3	Frequency stability	±2.5 ppm (-30°C÷+75°C)
2.4	Non - Spurious Dynamic Range	55 dB
2.5	Reference frequency	19 MHz
2.6	Phase tuning range	0÷360°
2.7	Phase tuning increments	11.25°
2.8	«Ref. Out»	square0 4 V p-p
2.9	«Output 1», «Output 2»	~0.5 B
2.10	Current demand	0.4A (+5V) 0.37A (+12V) 0.2A (-12V)

2.3.3. Front panel

On the front panel there is the following :

Indication

- «W/R» - reference to the writing/reading module

Outputs

- «Ref. Out» - monitoring output of a frequency of 30.0000 MHz
- «Output 1» - output of channel 1
- «Output 2» - output of channel 2

2.3.4. Control over the module

Address (dec)	Operation	Instruction	Monitoring signal
0	read	Reading of the byte of the last recording	
1	write	Recording of the byte to synthesizer 1	W_S1
2	write	Recording of the byte to synthesizer 2	W_S2
3	write	Recording of the byte to synthesizers 1, 2	W_S1+ W_S2
8	write	Reset of synthesizers 1, 2	SY_RST
11	write	Data updating in channels 1, 2	FQ_UD

A variant with the short addressing A16 is realized in the module. Code of the address modifier is 0x2d.

The low addresses A1-A7 are decoded. The high addresses (A8-A15) in the VME address space are assigned by the jumpers J1÷J8.

A15	A14	A13	A12	A11	A10	A9	A8
J8	J7	J6	J5	J4	J3	J2	J1

«0» – the jumper is ON
«1» – the jumper is OFF

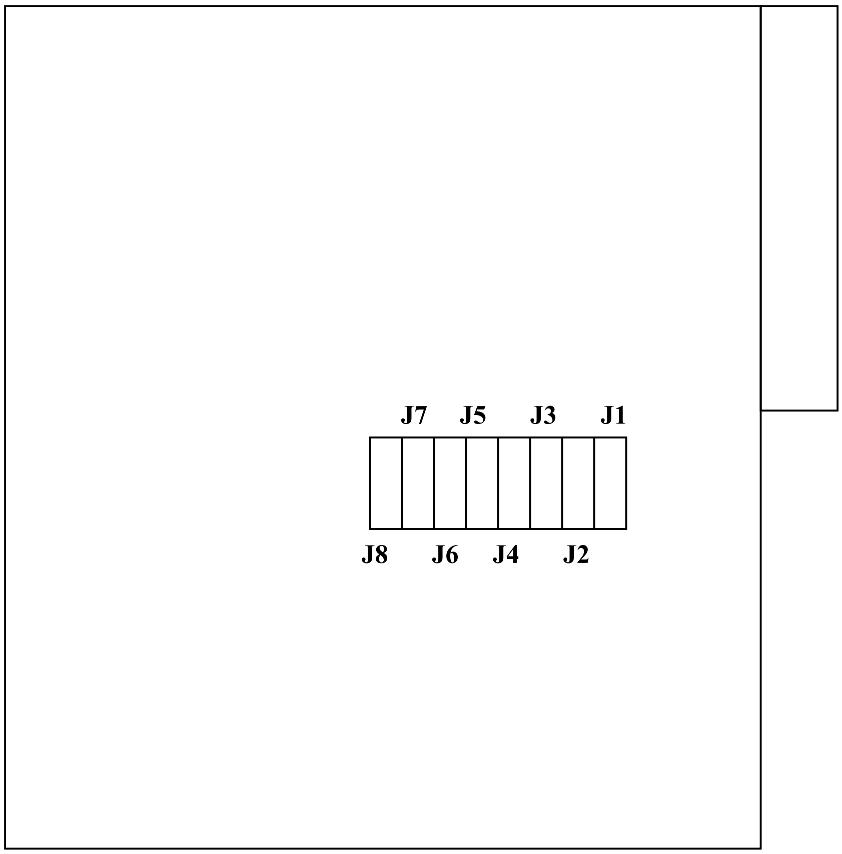

Fig. 8. Positions of jumpers on the board.

2.3.5. Operation of the module

A block diagram of the synthesizer is presented in Fig.5. Two identical channels for formation of the signal are clocked by reference frequency F_{ref} =19MHz from the common stabile reference frequency generator. Matching with the VME bus, control and synchronization of the channels are performed through the interface part.

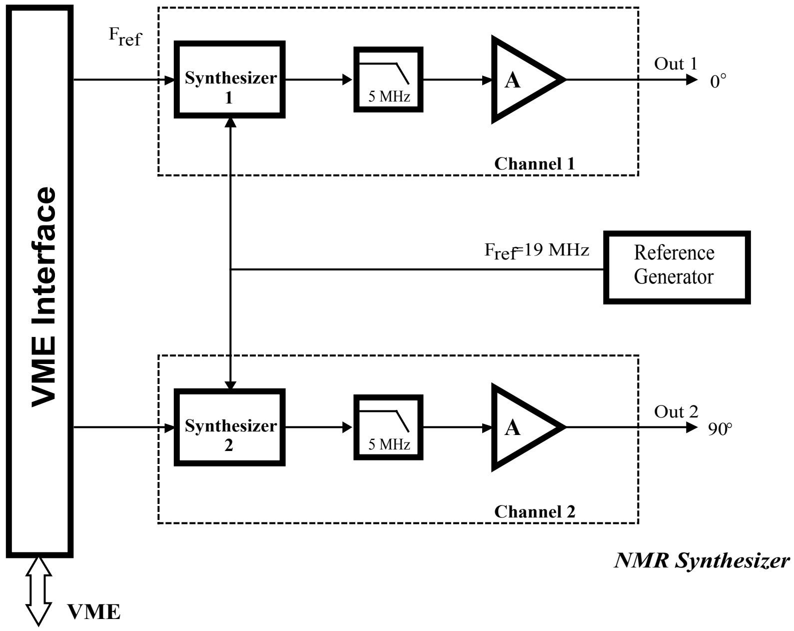

Fig. 9. Block diagram of the two-channel frequency synthesizer.

In both the channels (Channels 1 and 2), formation of a signal of an assigned frequency is performed by the microcircuit of the direct-synthesis synthesizer AD9851BRS (Analog Device). Characteristics of the microcircuit determine also the qualitative parameters of the synthesizer block as a whole. The microcircuit is a complete frequency synthesizer. It contains a circuit of direct frequency synthesis (DDS), the interface part for loading frequency and phase codes, reference frequency input, sixfold multiplier of reference frequency and input of setting of the output signal amplitude. Clock frequency of the DDS is a reference frequency of 19 MHz. This allows a maximal operational frequency of ~5 MHz at the output of the microcircuit.

Since both channels are identical, we'll illustrate their functioning by operation of channel 1. The signal from the microcircuit output is filtered by the low-pass filter with a cut-off frequency of 5 MHz and arrives to the input of the buffer amplifier **A**. The amplifier provides carrying a 50 Ohm load.

Circuits for control and synchronization of channels (Fig. 6) allow independent recording of frequency, phase and amplitude to each of channels as well as synchronization of the operation in order to achieve the assigned phase shift between the channels.

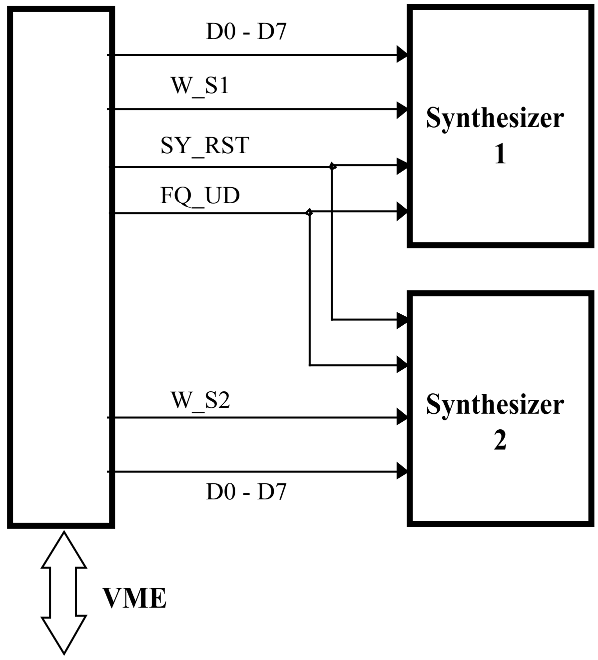

Fig. 10. Signals of control and synchronization of channels

The interface part AD9851BRS allows recording of a code (40 bits) to the buffer register of the microcircuit through the serial port or by 5 bytes through the parallel port. In this case, parallel loading of data is applied. Writing of bytes (bus D0÷D7) is synchronized by signals W_S1 and W_S2, formed by the control circuit for the first and second channel, respectively. Formation of the output signal corresponding to the data written starts after re-writing of them from the buffer register to the operational registers by the signal FQ_UD. This signal is common for both the channels, which allows synchronization of them.

To obtain a fixed phase shift between the channels which corresponds to the data written it is necessary to assign zero initial conditions. It is provided by the common reset signal SY_RST, which sets the operational frequency and phase registers to zero (not affecting the buffer registers), setting 0 Hz and 0° for the output phase. However, this isn't enough to set the right phase shift. The matter is that at the same time the SY_RST switches off the internal multiplier of reference frequency. The multiplier is built by the phase-lock loop and has a noticeable stabilization time (about 15 μs).The multiplier is turned on by the signal FQ_UD. A phase disbalance takes place due to different times of stabilization of the phase-lock loop. This leads to an indefinite phase shift. To obtain an assigned phase shift (90° for the magnetometer), the following writing procedure is used. After the initial reset, initial frequency and phase equal to zero are written down and after completion of the stabilization time the operational data are written down. 5 bits in the microcircuit of the synthesizer are used for setting of the phase shift, which determines a discreteness of 11.25°.

The frequency and phase codes are written down to each of the channels by five bytes of the following format:

Word	D7	D6	D5	D4	D3	D2	D1	D0
W0	P4 (MSB)	P3	P2	P1	P0 (LSB)	0	0	1
W1	F31	F30	F29	F28	F27	F26	F25	F24

	(MSB)							
W2	F23	F22	F21	F20	F19	F18	F17	F16
W3	F15	F14	F13	F12	F11	F10	F9	F8
W4	F7	F6	F5	F4	F3	F2	F1	F0 (LSB)

(W0 - phase, W1-W4 - frequency).
Sequence of the writing-down in each of the channels should be as follows:
W0⇒ W1⇒ W2⇒ W3⇒ W4

The interface part of the module performs matching with the VME bus, decoding of commands and control over the synthesizer channels. The main logical part of the interface is made by a programmable microcircuit EPM7064SLC (ALTERA).

2.4. PROBE MULTIPLEXER

2.4.1. DESTINATION.

12-channel Probe Multiplexer is intended for multiplexing of 12 Preamplifiers and probes. Multiplexer also provide supplying of the Preamplifiers and galvanic isolation of it from VME ground on the voltage 500 V.

2.4.2. PARAMETERS.

2.1	Number of channels	12
2.2	Attenuation in the range 1-80 MHz not more than	2 Db
2.3	Maximal signal multiplexed in the range 1-80 MHz	15 V
2.4	Isolating between channels in the range 1-80 MHz not worse than	60 Db
2.5	Isolating voltage between output connectors and VME ground	500 V
2.6	Control voltage of the digital input	TTL level
2.7	Module dimension	1 size
2.8	Consumption	
	+5 V	0.5 A
	+12 V	0.2 A

2.4.3. FRONT PANEL

There are 1 connector of the LEMO type and 13 connectors of the SMA type on the front panel.

Name of the connector	**Connector type**	**Destination**
«INPUT1» ÷ «INPUT12»	SMA	analog inputs (connected with Preamplifiers)
«OUTPUT»	SMA	analog output
«Strobe»	LEMO	digital input of the control signal

2.4.4. FUNCTIONS OF THE MODULE.

Address	**Function**	**word length**
0x0	Writing to the Channel register	4

4-bit word written to the Channel register corresponds to the Channel number (1÷12).

2.4.5. DESCRIPTION OF OPERATION.

A functional diagram of the NMR Receiver is depicted in Fig.11.

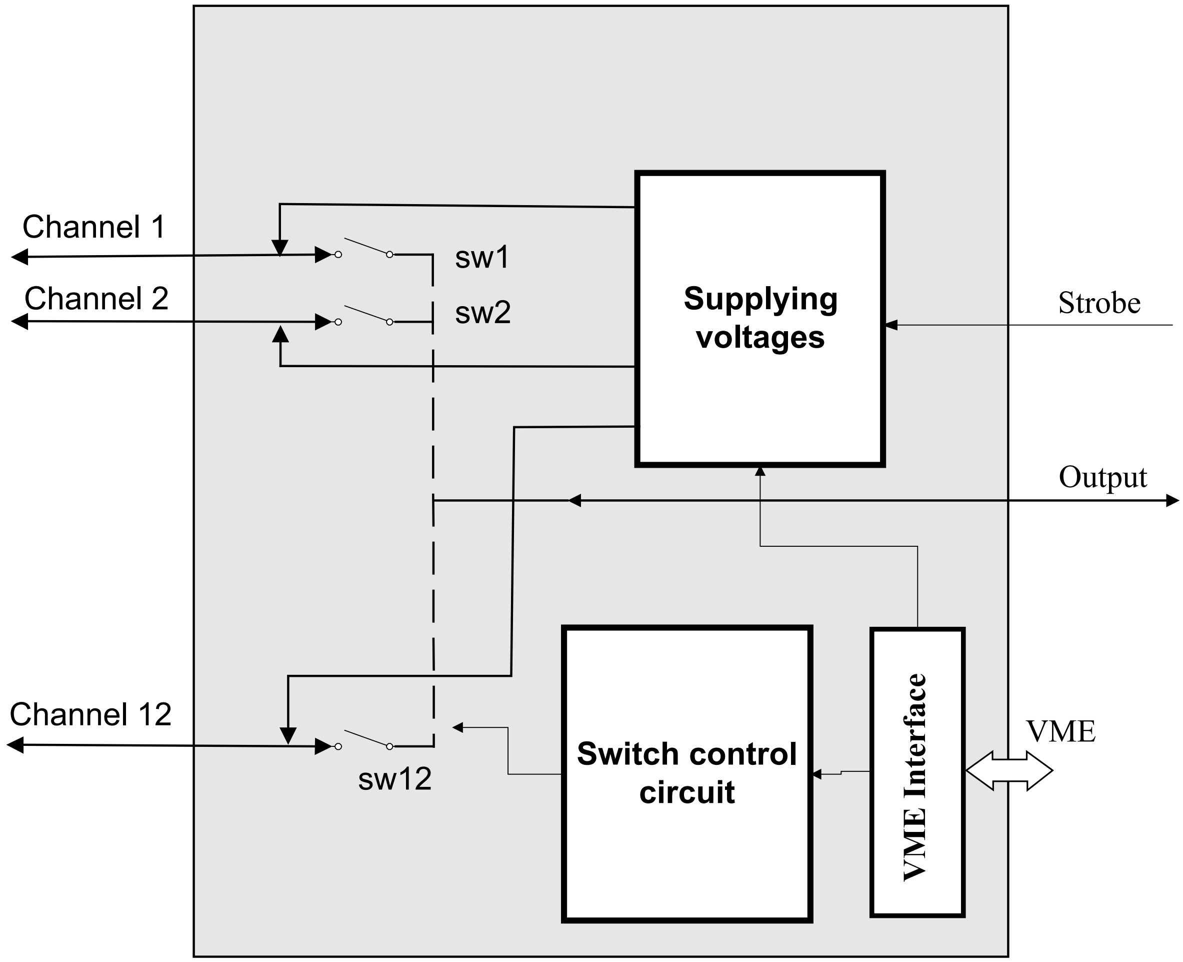

Fig. 11. Functional diagram of the Probe Multiplexer

Multiplexer consist of 12 P-I-N diode switches, switch control circuit and scheme of forming of supplying voltages for Preamplifiers. Since each Preamplifier is connected with corresponding Multiplexer input only with one cable it is necessary to deliver to Preamplifier besides of RF signals supplying voltages. Selection of the channel is carried out by writing of 4 bit code to Channel Register. Control voltage in the input “Strobe” provides transition of the Preamplifier from Reception mode to Transmission mode. In the Reception mode high level voltage is applied to the input “Strobe”, DC voltage +12 V is applied to selected channel input. Selected Preamplifier works as NMR signal amplifier. In the Transmission mode low level voltage applied to the input “Strobe”, DC voltage -12 V is applied to selected channel input. Selected Preamplifier transmits exciting RF voltage to the probe. All supplying voltages on the Multiplexer inputs are isolated from the VME ground on a voltage 500 V.

2.5. PREAMPLIFIER.

2.5.1. DESTINATION

The Preamplifier works as a part of the MNR System and is intended for primary amplification of the signal arriving from the NMR probe as well as for transmission of RF excitation pulses to the coil of the probe. The Preamplifier locates in the close vicinity to the NMR probe. This makes it possible to significantly move off the VME crate with the electronics from the site of measurement. The reason is that the signal arriving through the connecting cable from the Preamplifier to the “Probe Multiplexer” module in the VME crate is already amplified.

2.5.2. PARAMETERS .

2.1	Gain factor:	40 db
2.2	Bandwidth:	100 MHz
2.3	Input resistance	50 Ohm
2.4	Noise factor:	1.5 db
2.5	Time of switching from the transmission mode to the reception one (“dead time”):	100 μs
2.6	Supplying voltages:	
	in the Reception mode	+12 V
	in the Transmission mode	-12V
2.7	Dimensions	105×50×22 mm
2.8	Consumption +12 V -12 V	 40 mA 20 mA

2.5.3. CONNECTORS.

There are 2 connectors on the body of the Preamplifier:
- connector of the SMA type “INPUT” in the first side of the body
- connector of the SMA type “OUTPUT” in the second side of the body

Connector “INPUT” is connected with the probe. Connector “OUTPUT” is connected with the selected input of the Probe Multiplexer.

2.5.4. DESCRIPTION OF OPERATION

A functional diagram of the Preamplifier is presented in Fig.12. The Preamplifier contains a low-noise amplifier and RF switches with control circuit.

In the reception mode DC voltage of +12 V is applied to the output of the Preamplifier. Switches SW1, SW2 are in upper positions with such voltage. The low-noise amplifier amplifies the signal from the NMR probe and transmits the amplified signal to one of the inputs of the "Probe Multiplexer" module.

In the transmitter mode DC voltage of -12 V is applied to the output of the Preamplifier. Switches SW1, SW2 are in lower positions with such voltage. The Preamplifier transmits the excitation pulses arriving from the "Probe Multiplexer" to the coil of the NMR probe.

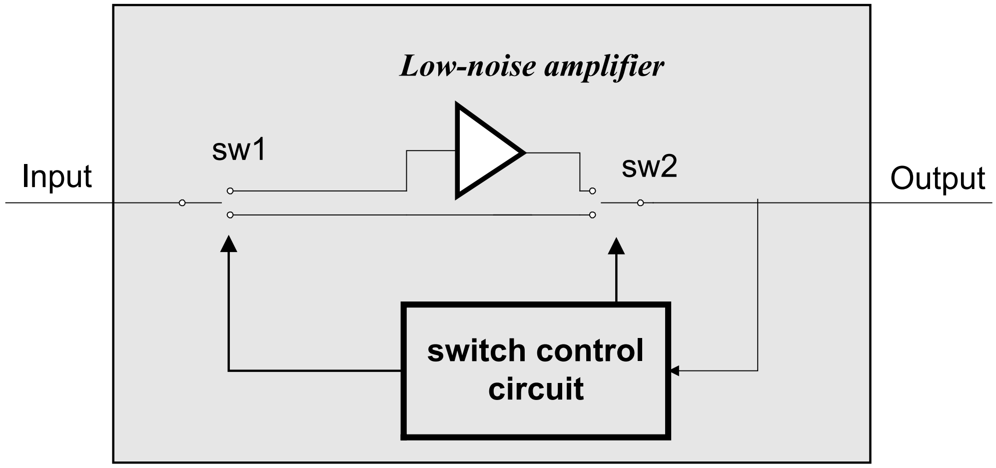

Fig. 12. Functional diagram of the Preamplifier.

2.6. NMR PROBES.

2.6.1. PARAMETERS .

2.1	Inductance of the coil:	13 μH
2.2	Field range:	270÷2000 G
2.3	Working nuclei	hydrogen
2.4	Gyromagnetic ratio:	42.57639 MHz/T
2.5	Relaxation time	30 ms
2.6	Sensitive area	5×5×10 mm
2.7	Body dimensions	9.5×15×35 mm
2.8	Consumption +12 V -12 V	 40 mA 20 mA

2.6.2. SHORT DESCRIPTION.

Electrical scheme of the NMR probe is represented in Fig.13. The probe consist of glass ampoule filled with weak solution of the copper sulphate with winded on it a coil, corrective capacitance and body with SMA-type connector. Hydrogen nuclei are used in the probe. Relaxation time depends on concentration of the copper sulphate solution and is chosen 30 ms.

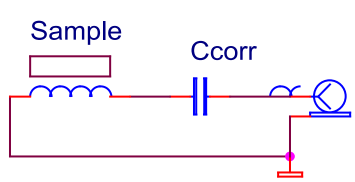

Fig. 13. Electrical scheme of NMR probe.

PART 3. EXPERIMENTAL RESULTS.

In accordance with ACCORD performance requirements NMR system have to provide relative precision and repeatability 10 ppm in 0.1 Hz bandwidth and 30 ppm in 1 Hz bandwidth in field range of 270-500 Gs. This precision should be realized under the condition that the field gradient at the NMR probe position should be less than 100 ppm/cm.

The main factors defined relative precision of measurements:

1) Stability of the synthesizer frequency
2) Field gradient at the NMR probe position
3) Signal-to-noise ratio
4) Time of field measurements (number of storages of the signal)

Stability of the synthesizer frequency is defined by Quartz oscillator frequency stability and is equaled 3 ppm in the temperature range -20÷+70 °C.

Signal-to-noise ratio depends on the probe and Preamplifier design and strongly depends on the field value. Signal-to-noise ratio increases with increasing of the field B almost as B^2. Therefore the most difficult problem is achieving of the required precision at lower part of the field range.

For experimental testing of the NMR system magnet with field 320 Gs made with permanent magnets have been used. NMR signal in this field is represented in Fig.14.

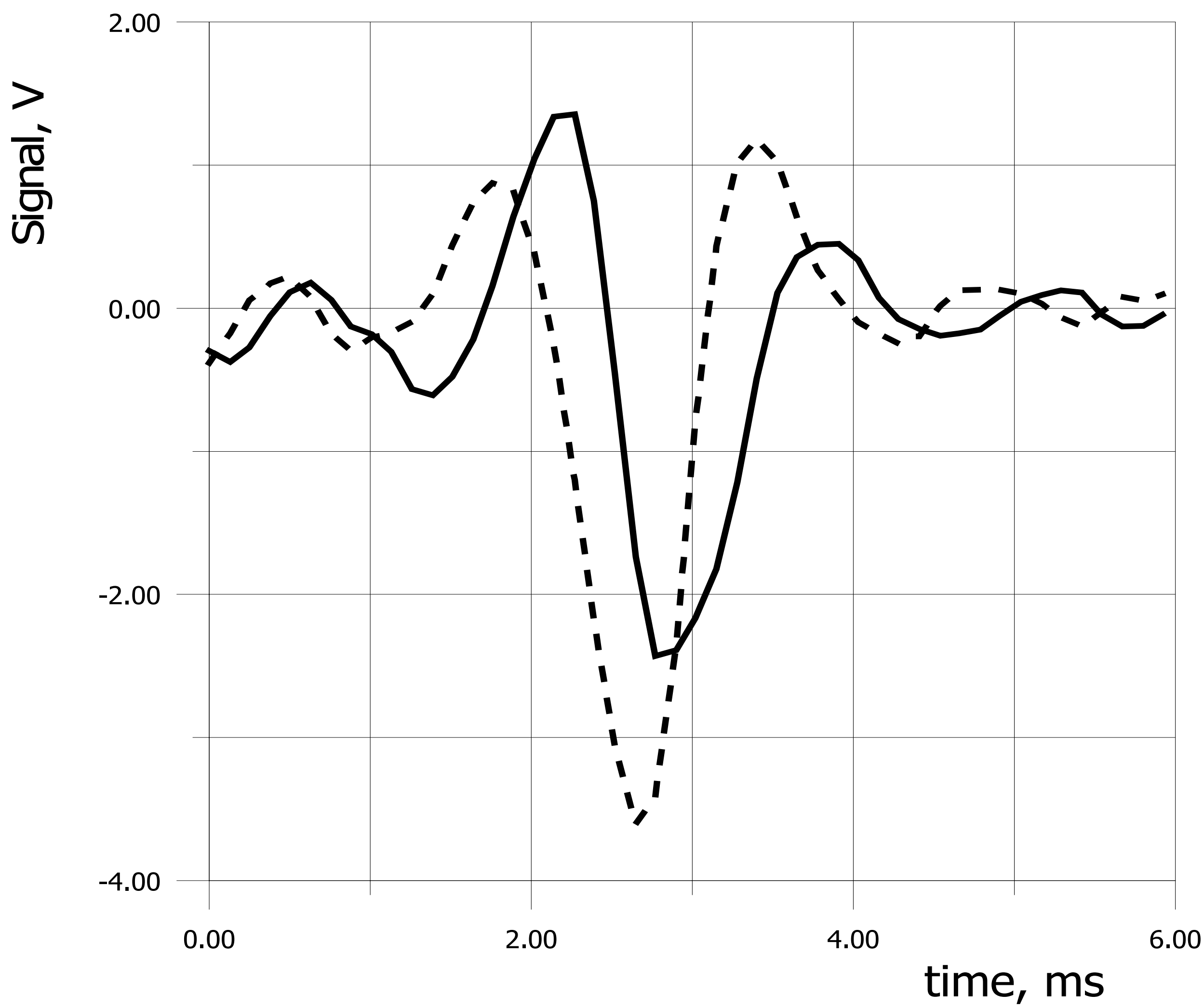

Fig. 14. NMR signal for the field B=319 Gs with 50 storages of the signal.

Two signals represented in this Figure are the signals on the outputs of the channel COS and SIN. A frequency of these signals is the difference frequency $F_d = F_{NMR} - F_{synt}$. Signal-to-noise ratio with one storage of the signal is about 3. With 50 storages of the signal signal-to-noise ratio is increased to 18÷20. Time required for 50 storages of the signal is about 5 sec under condition that only one probe is working. Time about 100 ms between storages (elementary cycles) is necessary for recovery of the nuclear magnetization of the probe sample (relaxation time is about 30 ms). In Fig.15 the spectrum of this signal is represented.

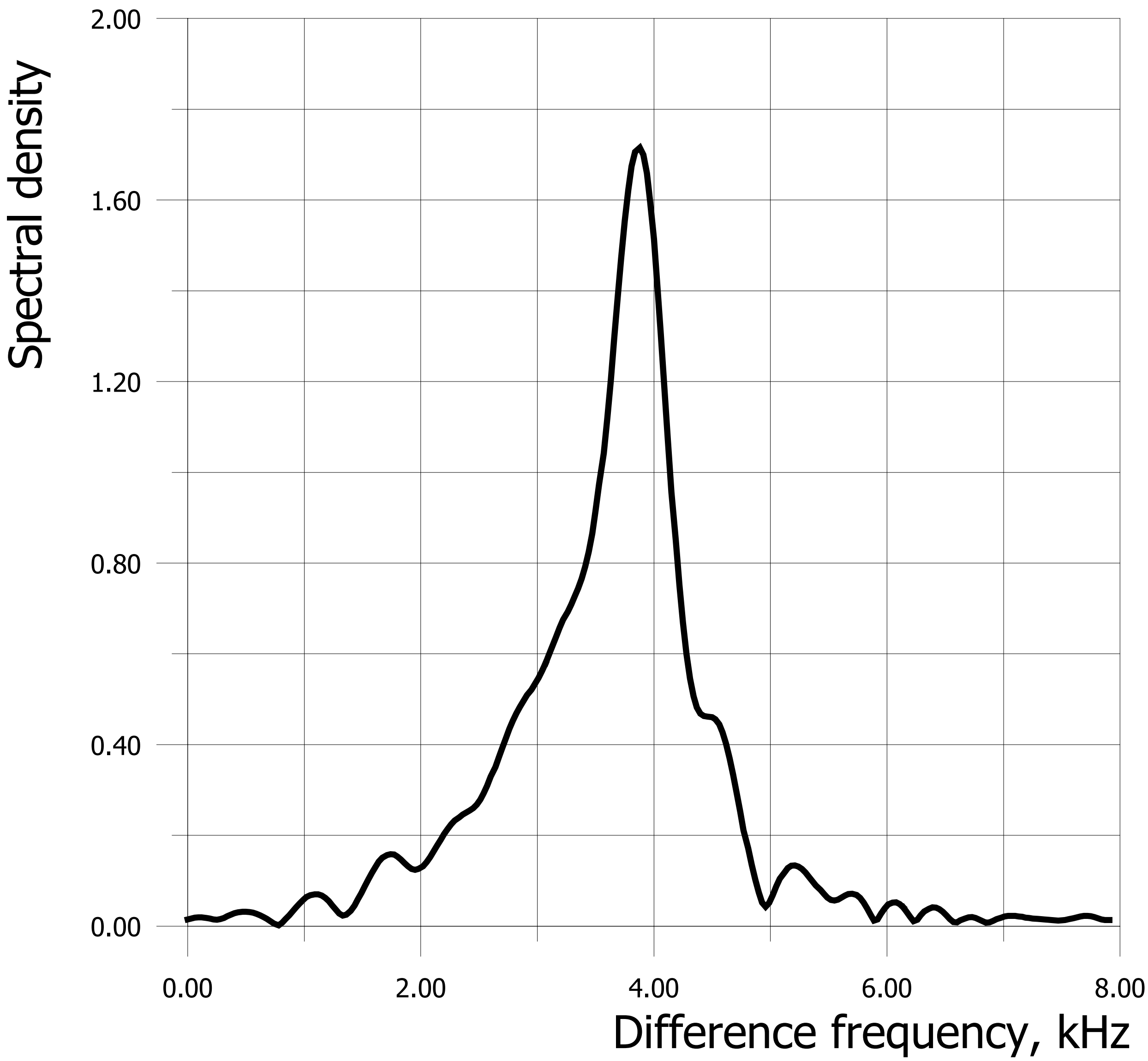

Fig. 15. Spectrum of NMR signal for the field B=319 Gs with 50 storages of the signal.

Width of this spectrum (NMR linewidth) is defined by homogeneity of the field at the probe position. In Fig.15 this linewidth is about 680 Hz. This value corresponds to field gradient at the probe position 0.16 G/cm or 500 ppm/cm if the gradient is directed along of axis of the probe coil.

Cyclical measurements of the field for a time 5÷10 min can show relative accuracy of measurements (for a short and middle time). In Fig.16 cyclical measurements of the field for a time 200 sec are represented.

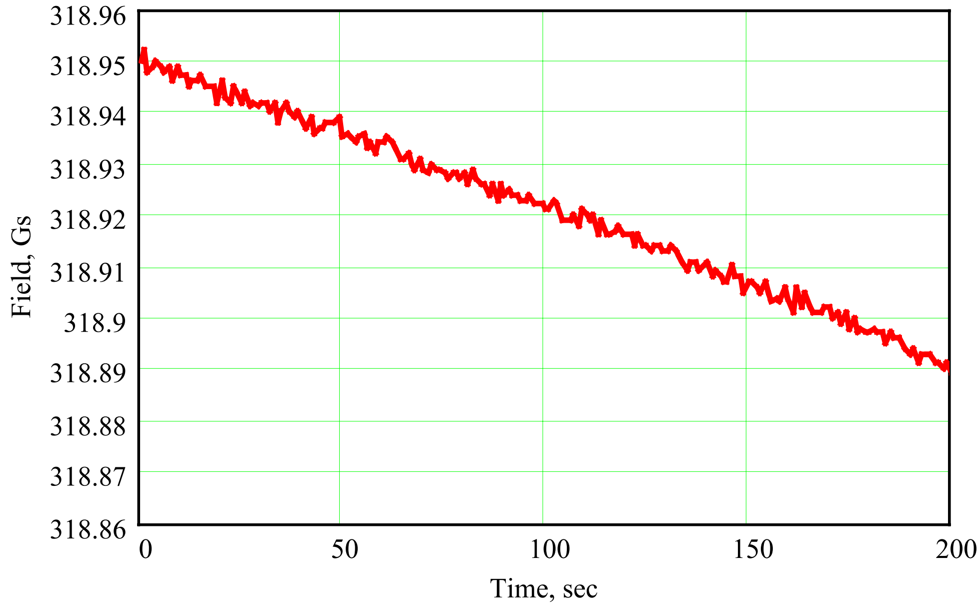

Fig. 16. Cyclical measurements of the field with 50 storages of the signal, field gradient is 500 ppm/cm.

Continuous decreasing of the measured field is caused by a large temperature coefficient of the permanent magnets. Since field of the permanent magnets is changed linearly with high order of accuracy one can exclude the influence of field changing by subtracting of the linear component of the function Field(t). Such modernized curve is represented in Fig.17.

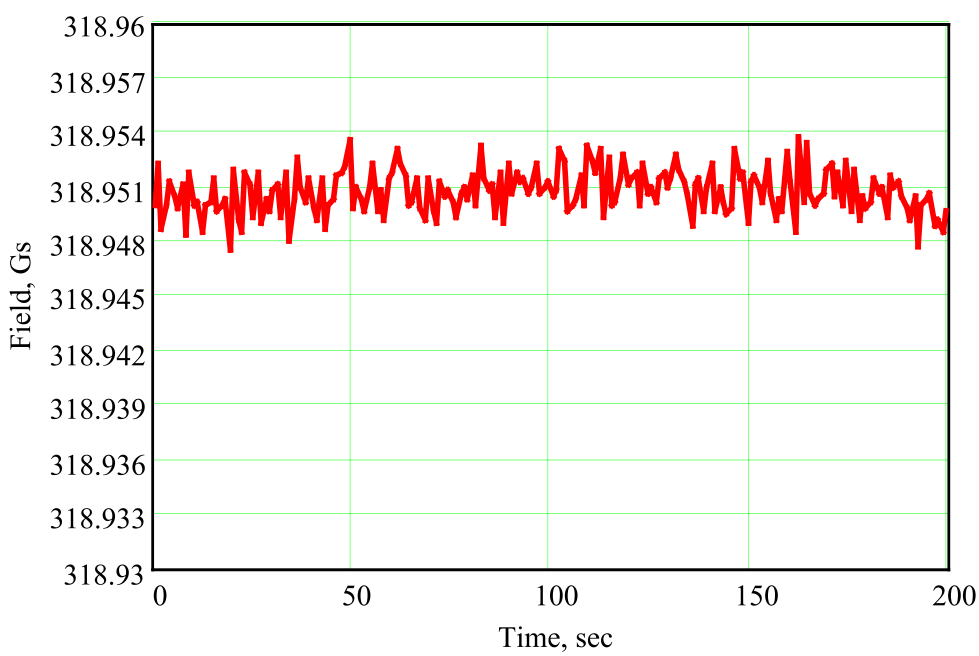

Fig. 16. Cyclical measurements of the field with 50 storages of the signal and excluding of the temperature field changing, field gradient is 500 ppm/cm.

As one can see at this picture relative accuracy of measurement with 50 storages of the signal during a time 3.5 min is about 10 ppm. For a long time relative accuracy will be approximately the same, only synthesizer frequency stability is added.

In Fig.17 analogues cyclical measurements of the field for a time 200 sec but with 10 storages of the signal (time of measurement is about 1 sec) are represented.

.

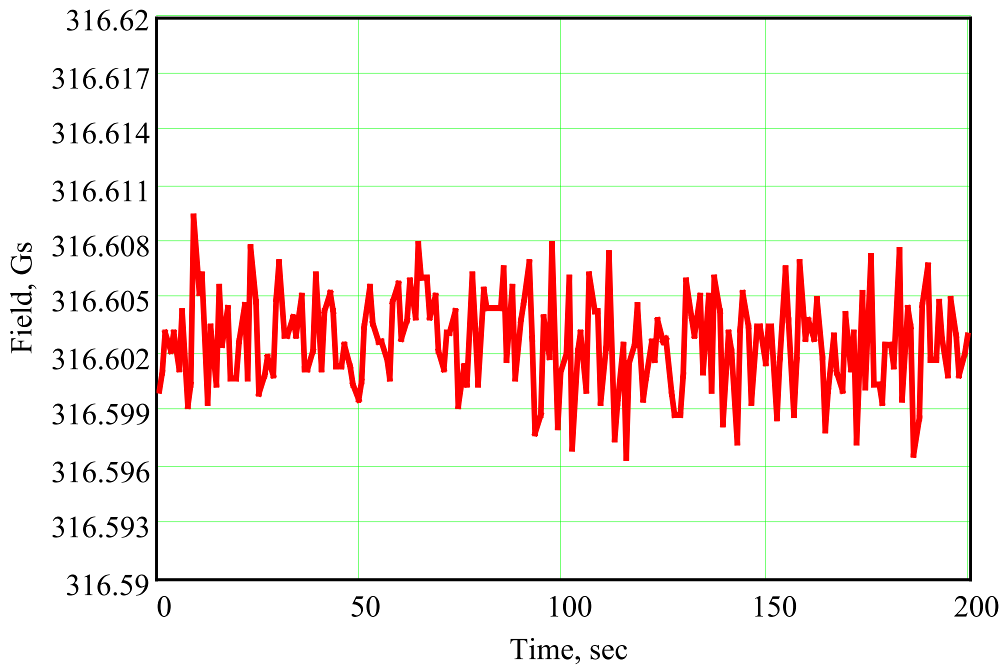

Fig. 17. Cyclical measurements of the field with 10 storages of the signal and excluding of the temperature field changing, field gradient is 500 ppm/cm.

As one can see at this picture relative accuracy of measurements with 10 storages of the signal during a time 3.5 min is about 20 ppm.

In Fig.18 cyclical measurements of the field for a time 200 sec with 50 storages of the signal but with worse field homogeneity (field gradient is 1000 ppm/cm) are represented. As one can see at this picture relative accuracy of measurements with 50 storages of the signal during a time 3.5 min with field gradient 1000 ppm/cm is about 30 ppm. It shows strong dependence of the measurement accuracy on the field homogeneity.

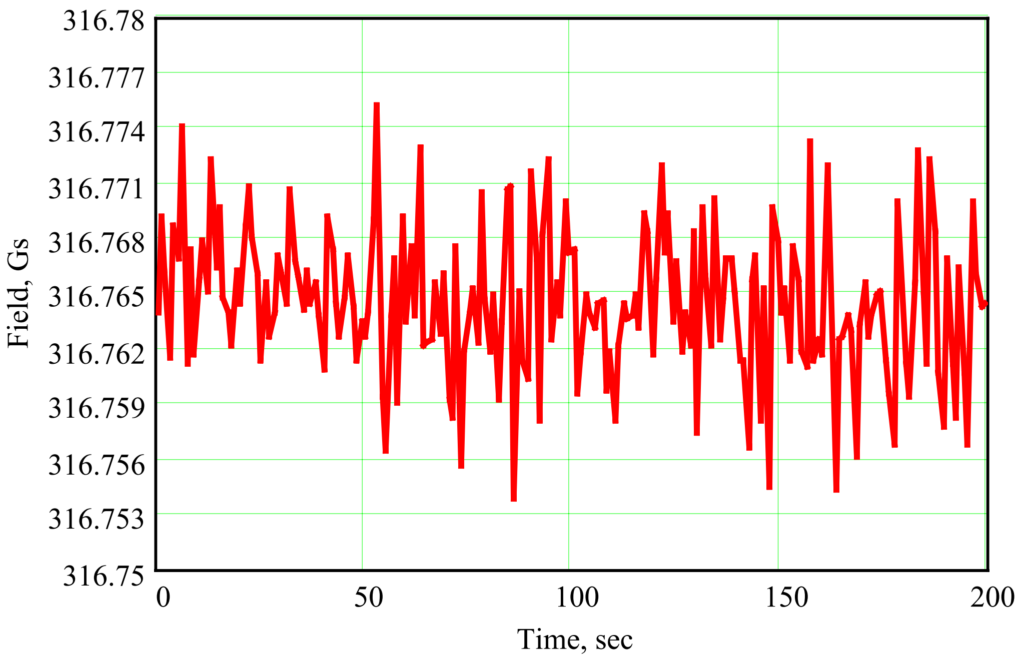

Fig. 18. Cyclical measurements of the field with 50 storages of the signal and excluding of the temperature field changing, field gradient is 1000 ppm/cm.

CONCLUSION.

As it was shown in part.3 developed NMR system is satisfied to main ACCORD requirements. This system allows to perform field measurements in the range 270÷600 G. Relative precision of 10 ppm with time of the measurement 5 sec for one channel has been achieved. Relative precision with time of the measurement 1 sec is about 30 ppm. Total time of measurement with 50 storages of the signal for all 12 channels is about 10÷12 sec. These parameters have been achieved with worse than it was specified in ACCORD field homogeneity. Field gradient in the test magnet was 500 ppm/cm that in 5 times more than it was specified in ACCORD. Repeatability of the field measurements besides of considering above depends on accuracy of fixing of the probe on the magnet pole. Field map of the designed magnets shows that this accuracy have to be better than 0.2÷0.3 mm in transverse direction.